Mechanical Technology Development on A 35-m Deployable Radar Antenna for Monitoring Hurricanes

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***Abstract* – The NEXRAD in Space project develops a novel instrument concept and the associated antenna technologies for a 35-GHz Doppler radar to monitor hurricanes, cyclones, and severe storms from a geostationary orbit. Mechanical challenges of this concept include a 35-m diameter lightweight in space deployable spherical reflector and a feeder scanning mechanism. The feasibility of using shape memory polymer material to develop the large deployable reflector has been investigated by this study. A spiral scanning mechanism concept has been developed and demonstrated by an engineering model.**

I. INTRODUCTION

Under NASA's Earth Science Technology Program, a novel instrument concept and the associated antenna technology are being developed for a 35-GHz Doppler radar for detailed monitoring of hurricanes, cyclones, and severe storms from a geostationary orbit. This instrument is named as "NEXRAD in Space (NIS)". The objectives of the NIS project include measuring hurricane precipitation intensity (quantitative rainfall rate), dynamics, and life cycle, thus providing temporal information critical for creating advanced warning systems and improving numerical model prediction of track, intensity, rain rate, and hurricane-induced floods. The practical benefits derived from this kind of space system such as enhanced public safety, better emergency response and mitigation of property loss and economic impacts are evidently clear.

NIS is designed to operate in the geostationary orbit at an altitude of 36,000 km. The NIS antenna subsystem is composed of a deployable 35-m diameter spherical reflector and two sets of feeders. Each set of feeder has one feed for signal transmission and another feed for echo reception. Both the reflector and the spacecraft will remain stationary as the feeders perform spiral scan maneuvers up to 4^o to cover a 5300-km circular area on the Earth surface [1, 2].

A space deployable 35-m diameter reflector that operates at 35-GHz with 0.17 mm RMS surface accuracy requirement is beyond the current state-of-the-art. It is impracticable of using a single-launching system to launch a 35-m reflector with currently available space deployable structures technology. In order to implement NIS, several innovative space structures technologies have been investigated and will be discussed by this paper. Emphasize will be on the reflector development using the novel Shape Memory Polymer (SMP) material. SMP made it possible that the 35-m reflector along with the spiral feeder system (that is located 27.56 meter away from the reflector) and the spacecraft to be packaged into a Delta II launch vehicle. Another mechanical sub-system that will be discussed in detail by this paper is the spiral scanning feeder system. The feasibility of the NIS instrument on the mechanical aspect will be demonstrated and further developing directions will be identified by this paper.

II. SHAPE MEMORY POLYMER ANTENNA

Shape Memory Polymer materials are the state-of-the-art materials with a broad range of very unique characteristics that can be utilized for future development of ultra lightweight, extremely large, high-precision, high-packaging efficiency space structures. SMP materials retain memory of their as-manufactured state. When heated to above their glass transition temperature (Tg), they become pliable and can be compactly packaged. Upon cooling, SMP materials retain their packaged state; but when reheated to above their Tg, they become pliable and deploy back to their original shape. This unique characteristic of SMP material is extremely suitable for developing high-precision deployable reflector antennas.

A very sophisticated study has been performed by ILC Dover and JPL to investigate the feasibility of using SMP materials to develop the high precision 35-m diameter reflector [3]. This study was initiated with a brainstorming session which was conducted by engineers and researchers experienced in this technology area to flush out innovative ideas. Seven concepts were developed from these ideas and a list of trade parameters were established for a trade study. These trade parameters are:

- Reflector surface accuracy—the ability of the reflector surface to achieve and maintain the desired shape (after deployment and rigidization) in the operational environment. Surface material and attachment

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configuration are significant contributions to surface accuracy.

- Support structure accuracy—the ability of the structural components to achieve and maintain dimensional accuracy and position and provide structural stiffness in the operational environment. Structural material, attachment configurations, packing and deployment configurations are significant contributions to structural accuracy.
- Controlled deployment—the ability to be deployed (multiple times) in a controlled and predictable fashion. Controllability means the ability to deploy the system in a smooth and reliable fashion without causing reflector and structure damage and unwanted loads to the spacecraft. Predictability means the ability to know where the deploying components are at any moment of the deployment process. Packing and deployment architectures, attachment method, and number of parts are primary contributions to deployment control.
- Packing—packing parameter has several sub-categories: (1) the ability to fit within the defined launch vehicle, (2) compatible with the launch vehicle (particularly launch restraint issue), (3) compact ratio, (4) easy of packing, and (5) friendliness of packing method (dealing with potential damage or degradation due to multiple packing and deployment).
- Mass—the ability to achieve operational requirements within the budgeted mass
- Scalability—a scalable concept could be enlarged or reduced in size with little or no reconfiguration. Scalable also means the concept can be scaled down for test and scale up for potential missions.
- Ground testability—ease to conduct ground testing for system validation which includes (1) 1-g deployment (is g-negation system required?), (2) support equipment for ground testing, and (3) antenna accuracy under 1-g environment.
- Design flexibility—the ability to adapt to alternative design options (materials and/or configurations).
- Complexity/reliability/risks—it evaluates the mission risks. It is based on preliminary parts count and maturity (TRL) level of each technology. The higher parts count means higher complexity and lower reliability.
- Cost—the ability to achieve all operational/mission requirements within the budgeted cost.

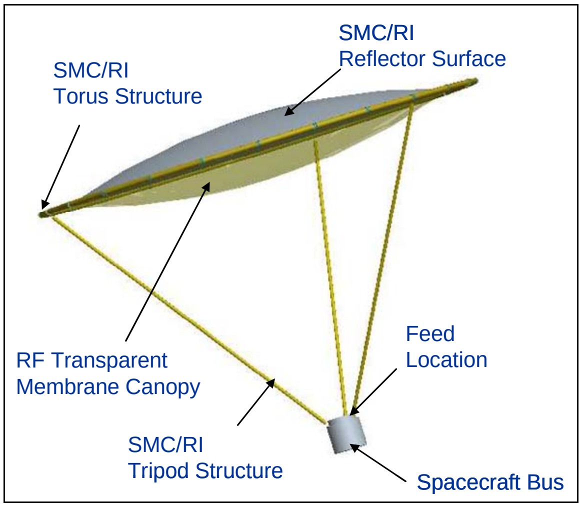

Fig. 1. Schematic view of the antenna

After the trade study, the best architecture as shown in Fig. 1 has been identified. The spherical reflector of this architecture is composed of Shape Memory Composite/Rigidizable-Inflatable (SMC/RI) with a RF transparent membrane canopy. The RI reflector is supported by a SMC/RI perimeter torus. The reflector system is connected to the spacecraft bus via the tripod structure. The feed system is located on spacecraft bus. The whole antenna can be packed into a 2.0-m diameter and 2.5-m high cylinder.

Figs. 2 demonstrate the deployment process of the antenna. The first step of the deployment is to heat all deployment elements above their glass transition temperature. The second step of the process is the inflation deployment of the tripod. Both the reflector and the torus structure are slowly unfurled by the material's shape memory force as well as the tripod pulling force. The third step of the deployment process is to inflate the torus structure and the reflector after the tripod is fully deployed. Although the material has the shape memory capability, inflation is still necessary during the deployment process to guarantee a fully deployment. The material's shape memory force is relatively week, it may not be sufficient to assure a fully deployment. The inflation force completes the global deployment by bringing every deployment element to its expected location. The forth step of the deployment process is vent all the pressure. During this step, the shape memory capability of the material brings the whole system back to the as-fabricated shape. The inflation force completes the global deployment and the shape memory capability offers high local precision. Therefore, the SMP material makes the extremely large and high precision in space deployable antenna possible. The last step of the deployment process is to reduce the temperature to the material glass transition temperature to rigidize the antenna system.

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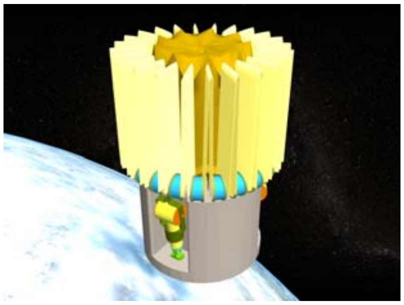
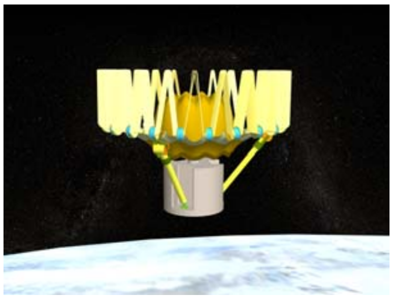
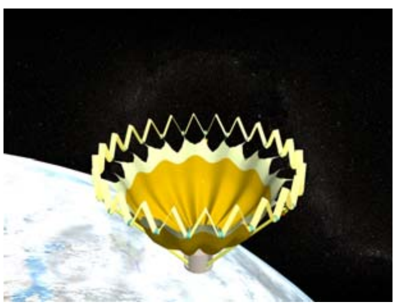


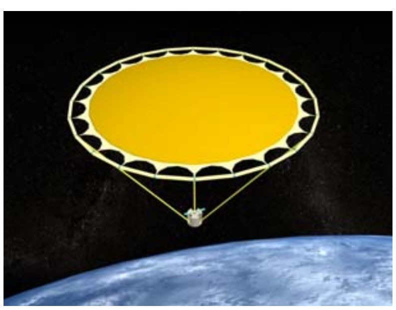
(a) System is in stowed configuration. Deployment elements are being heated to above the glass transition temperature.



(b) Tripod is slowly inflated to deploy. The torus structure and the reflector are unfurled correspondingly.



(c) The reflector and the torus structure continue to deploy. The deployment process is guided by the inflation deployment of the tripod.



(d) System is fully deployed. Toward the end of the deployment, the torus structure and the reflector are inflated to assure the global shape return.

Fig. 2. The deployment process

This concept was refined with more detailed preliminary design and analyses [3]. Preliminary design and analyses included (1) material identification and evaluation, (2) preliminary mass analysis, (3) preliminary antenna reflector accuracy analysis (including prediction for both active tuning and no tuning cases), (4) deployed and stowed configuration (including preliminary deployment animation), and (5) stowed volume. It has been concluded by this study that Shape Memory Polymer reflector is feasible and attractive. Shape memory "rigidizable" is a key enabling technology which will make future extremely large and high packaging efficiency deployable reflectors possible. Further material developing directions include CTE reduction and heater power reduction.

III. FEEDER SPIRAL SCANNING MECHANISM

The NIS instrument employs a novel observational architecture. For this architecture, both the reflector and the spacecraft will remain stationary as the antenna feeds perform spiral scan maneuvers up to 4^{o} to cover a 5300-km circular disk on the earth surface. This spiral scan approach allows continuous and smooth transition between adjacent radar footprint coverage. One complete disk scan will take a total of 200 spirals.

The first step of developing this scanning mechanism is to establish several scanning mechanism architectures. The first architecture is named as Helix Track as shown in Fig. 3a. It is composed of a helix track with a trolley that moves linearly on the track. There are two feeds on the trolley, one for signal transmission and another one for echo reception. Fig. 3b is the Earth surface coverage pattern of this scanning mechanism.

Fig. 3a. Helix Track architecture

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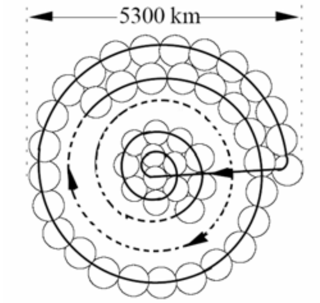

Fig. 3b. Illustration of Earth surface coverage pattern of the Helix Track architecture

The Helix Track architecture has several drawbacks: (1) it is very difficult to implement because there are 200 spirals within a given diameter; (2) it introduces some RF blockage; (3) it is not easy to package and deploy this system for space launch; (4) quick return of the trolley to the center from the outer end of the spiral track is a challenge.

The second scanning mechanism is named as Double Rotating Bars as shown in Fig. 4a. It is composed of two rotating arms and every rotating arm rotates at a constant rotational speed. The first bar rotates about the fixed axis and the second bar is connected to the other end of the first bar and rotates with respect to the connecting point. Two sets of feeders (each set has one feed for signal transmission and another feed for echo reception) are placed at the two ends of the second bar. Fig. 4b gives the surface coverage patterns of the Double Rotating Bars architecture, from just started to scan (left) to almost finish the scanning (right).

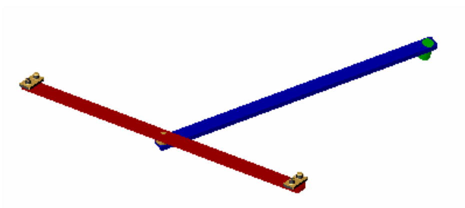

Fig. 4a. Double Rotating Bars architecture

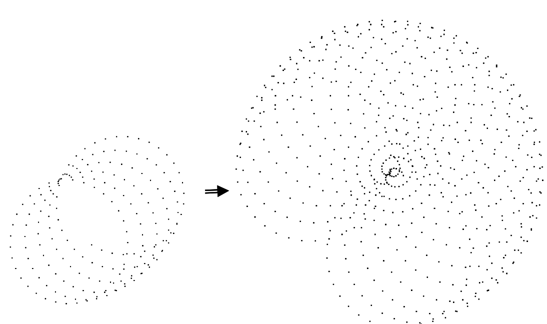

Fig. 4b. Illustration of surface coverage patterns of the Double Rotating Bars architecture. Left is just start and right is almost finish

The advantage of this architecture is both bars rotate at constant speeds. However, this architecture generates some unbalanced inertial force. This inertial force makes this architecture to be not feasible since the spacecraft may not be able to balance this force.

The third scanning mechanism is named as Rotating Bar. It is composed of a rotating bar with a trolley that moves on the bar. A set of feeder with one transmission feed and one echo reception feed is on the top of the trolley. The combination of the rotational motion (bar) and the translational motion (trolley on the bar) gives a spiral motion. The Earth surface footprint pattern of this architecture is identical to Fig. 3b. This architecture also has the unbalanced inertial force which will be loaded to the spacecraft and introduce vibrations to the whole system.

In order to resolve this problem, the Rotating Bar architecture has been modified to have two sets of feeder. Instead of one spiral trace, two sets of feeder produce two parallel spiral traces as shown in Fig. 5. One advantage of using tow sets of feeder is the self-balance of the centrifugal forces created by feeders. No significant oscillatory forces will be loaded to the spacecraft anymore. Since two sets of feeder will double the footprints with every revolution, the spiral speed can thus be reduced to half. As a result of that, two sets of feeder offers a much quieter and smother scanning mechanism.

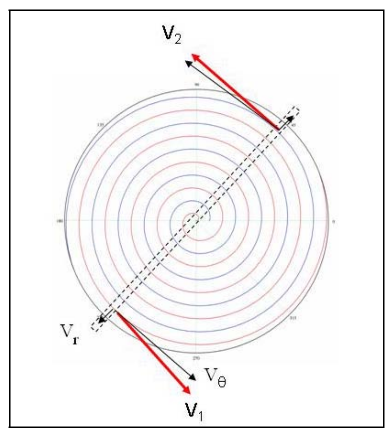

Fig. 5. Two parallel spiral traces as shown in

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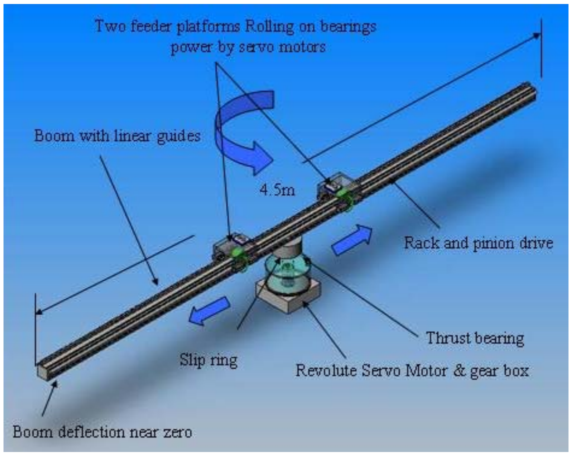

Fig. 6. Schematic view of the spiral scanning system

A full scale engineering model has been designed and fabricated for further develop the spiral scanning mechanism. Fig. 6 is the schematic view of this engineering model. A Bosch aluminum extrusion boom has been used as the rotating bar. Linear guides are attached to the boom to precisely guide the motion of the feeder platforms. Four highly lubricated Bosch linear bearings are used by each platform to move smoothly on the guides without any vertical motion. Translational motions of two feeder platforms along the boom are powered by two servo motors and gears. The combination of the boom rotational motion and platform translation motions generate two precise spiral trajectories at a constant speed. Feedback control systems are used for high precision speed and position control. Fig. 7 shows all the components of the spiral scanning system.

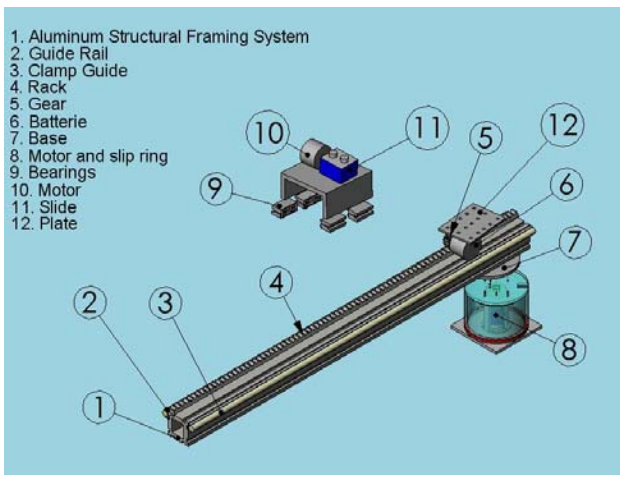

Fig. 7. Components of the spiral scanning system

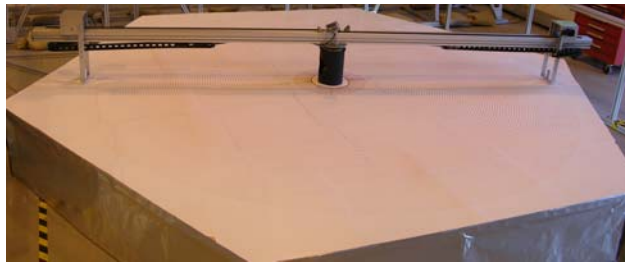

Fig. 8. A spiral scanning mechanism with the spiral traces created by this mechanism

To verify the design and analysis of this system, a full scale engineering model has been assembled as shown in Fig. 8. The spiral speed of a feeder platform has been measure by an independent measuring system and the result is given in Fig. 9. The average speed is 17.57 cm/sec with a velocity deviation RMS to be 0.026 cm/sec. Since the velocity deviation is only 0.15% of the average spiral speed, this engineering model satisfactory.

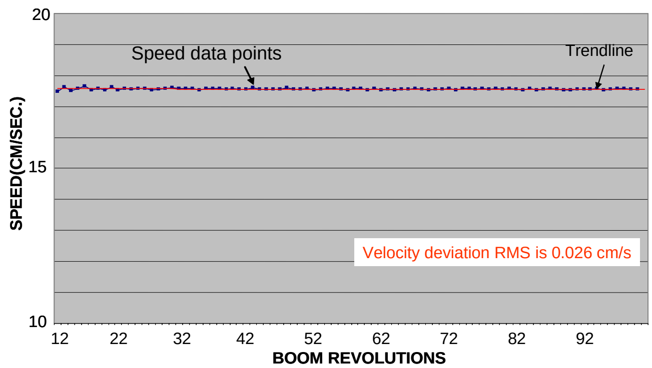

Fig. 9. Experimental result of the spiral speed

IV. CONCLUSIONS

It has been demonstrated by this study that using SMP material to develop an in-space deployable extremely large and ultra lightweight reflector is feasible and attractive. Further material developing efforts should include CTE reduction and heater power reduction. The high precision of spiral scanning mechanism developed by this study has been experimentally verified. As a conclusion of this study, the mechanical aspect of the innovate NIS instrument concept is feasible.

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This study is sponsored by ESTO, NASA

REFERENCES

[1] Im, Eastwood, Durden, S. L., Rahmat-Samii, Y., Lou, M. Huang, J., “Conceptual Design of a Geostationary Radar for Monitoring Hurricanes,” Jet Propulsion Laboratory, California Institute of Technology, Pasadena

[2] Im, Eastwood, Durden, S. L., “Spaceborne Atmospheric Radar Technology,” Jet Propulsion Laboratory, California Institute of Technology, Pasadena

[3] J. Lin, H. Fang, E. Im and U. Quijano, “Concept Study of a 35-m Spherical Reflector System for NEXRAD in Space Application”, AIAA-2006-1604, 47th AIAA/ ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Newport, Rhode Island, May 1-4, 2006

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